Vibration Measurement and Trend Analysis of a Light Transport Aircraft Engine

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***Abstract*—Vibration is an important parameter to judge the safety, integrity and efficiency of an engine installation in any aircraft. Certification authorities usually require proof that the engine installation meets the specified requirements of the engine Original Equipment Manufacturer (OEM). This paper describes a method for vibration measurement and trend analysis of a Light Transport Aircraft (LTA) turbo prop engine. In the process, a transducer mounting bracket is designed and analyzed for mode shapes using commercial software ANSYS and the results have shown that the natural frequency is within the safe limits. Architecture of the data acquisition system and the signal processing are clearly elaborated. The engine vibration level measured for different power settings on the aircraft is within the limits specified by the engine OEM. Thus, the vibration measurement system developed has been successfully meeting the requirement and the data is used for engine health monitoring.**

***Keywords*ð Vibration measurement, condition monitoring, data acquisition, signal processing, trend analysis**

I. Introduction

Mechanical vibration is a common phenomena observed in all rotating machines. These vibrations sometimes have harmful effects on the life of the equipment and also on its operational stability. Hence, knowledge of vibration is useful in design, construction, operation and maintenance of any structure or machine regardless of its area of application. Vibration signal trend monitoring and analysis can give early indications of developing faults in a component, thus alarming the user to take timely action and avoid production downtime, maintenance cost, catastrophic failure and also unsafe working environment[1,2,3].

In a modern aircraft, for production acceptance testing, for rapid identification of faulty components and also in the interest of future design efforts, a deep understanding of vibration measurements is desirable. This work has been carried out on a LTA installed with a turboprop engine. It is a lightweight turbine engine which drives a propeller to generate thrust (Figure 1). The two major sections of the engine are the compressor and compressor turbine and the power turbine and power turbine shaft. These two rotors can rotate at different speeds and in opposite direction and this configuration is called ófree turbine engineô [4]. Jesse De Priest, Lord Corporation [5] has discussed in detail the fundamental information about vibrations and its consequences, their treatment and preferred design approach in a modern aircraft. M Botman, 1980 [6] has reviewed a number of dynamic measurements on a PT6 aircraft engine reduction gearbox and analyzed the vibration data obtained. Vibration in rotating machines can be due to various causes like rotor unbalance, misalignment, mechanical looseness, wear and deterioration etc. Parameters of vibration measurement may be amplitude, frequency and phase. But even with modern instrumentation and enhanced analysis methods, accurate detection of the faults is still an inexact science. Also despite the significance of vibration measurement in rotating machinery, very little information is available in public domain probably due to its propriety nature.

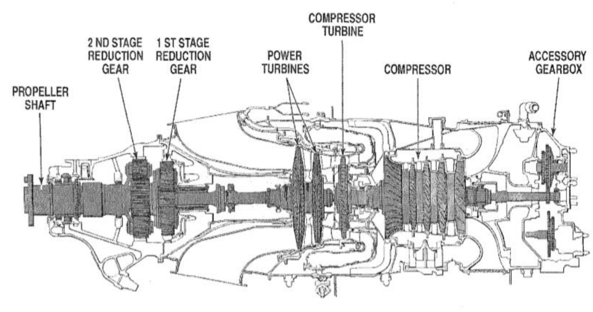

Figure 1 LTA turboprop engine ï components and construction [4]

II. Structure of Engine Vibration Measurement System

The architecture of the vibration Data Acquisition (DAQ) system employed is shown in the following block diagram (Figure 2).

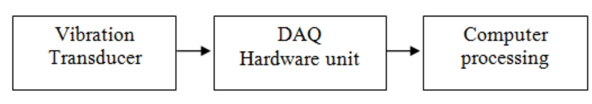

Figure 2 Structure of vibration measurement system

A. Vibration Transducer

Vibration can be measured as amplitude of displacement, velocity and acceleration. Here, an accelerometer is used as vibration transducer to capture high frequency signals generated by the engine. Endevco Isotron Model 751 (Figure 3), a piezoelectric type with integral electronics is the single axis accelerometer selected with the characteristics [7] as in TABLE I.

TABLE I
ACCELEROMETER SPECIFICATIONS

Input dynamic range	±10g
Frequency bandwidth	0 ï 50kHz
Sensitivity	2.011mV/g for ABO_LH
Output range	±10V

Figure 3 Endevco Isotron 751 accelerometer [7]

B. Accelerometer Mounting Technique and Location

The fidelity of the data acquisition mainly depends upon the transducer mounting technique and the mounting location. Stud mounting, magnetic mounting, adhesive mounting etc are a few techniques employed for installing the transducers. In the present work, stud mounting technique with the help of a mounting bracket is employed to have reliable and repeatable measurements even at high frequencies. Four accelerometers (A, B, C &D) are used as shown in Figure 4. Accelerometer A is mounted at the frame on the casing near the power turbines, accelerometers B & C are mounted adjacent to the reduction gearbox at 3 oôclock and 6 oôclock positions respectively and accelerometer D is mounted besides the accessory gearbox. Though the sensor mounting locations have been recommended by the OEM, effort has been made to understand the nuances of arriving at the optimum locations [9, 10].

C. Accelerometer Mounting Bracket

The accelerometer is mounted on the engine using a mounting bracket shown in Figure 5.

The bracket interfaces are designed so as to fit the mounting location at the engine. Also good surface contact is ensured for proper duplication of the vibration signals generated at the engine. The material of the bracket is Aircraft Material Specification (AMS) 5659. The mounting bracket serves as a connector between the engine and the accelerometer and is prone to very high vibration. Hence dynamic analysis of the bracket was carried out to arrive at a safe design.

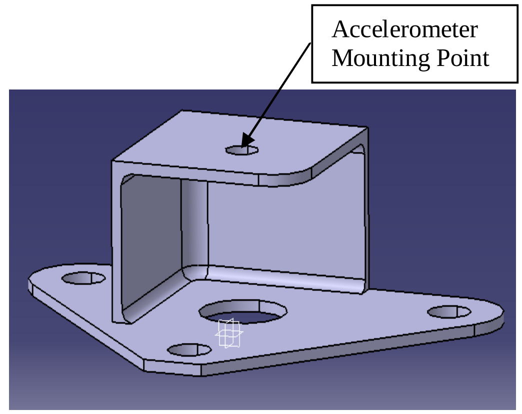

Figure 5 Accelerometer mounting bracket ï CATIA geometric model

D. Dynamic vibration analysis of mounting bracket

A normal modal analysis is carried out on the accelerometer mounting bracket to determine its vibration characteristics.

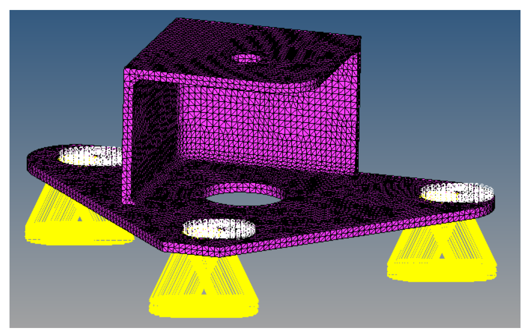

Figure 6 FE Model of accelerometer mounting bracket

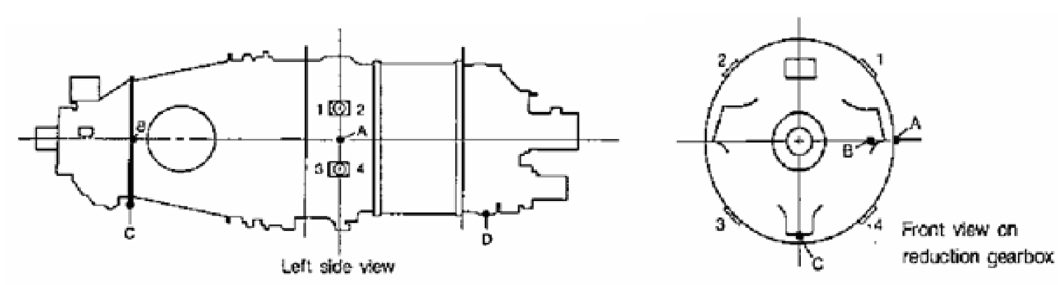

Figure 4 Accelerometer mounting locations [8]

The finite element modelling using 3D Solid 185 element was generated using Altair Hypermesh 11.0 (Figure 6). All Degrees of Freedom (DOF) were arrested at the three holes in the bracket to simulate tight clamping to the engine casing. Another case of simply supported (SS) boundary condition was also analyzed in order to simulate any loosening of clamping bolts. Dynamic Analysis of the mounting bracket was done using Ansys 13.0 commercial Finite Element Analysis (FEA) software which was used to solve and carry out post processing.

TABLE II
Modal frequencies in hertz

Mode	Natural frequency (Fixed)	Natural frequency (SS)
1	3961.4	2234.3
2	4864.3	4283.9
3	7070.5	5838.7
4	9696.0	6957.0
5	10540.0	9083.2
6	16477.0	10142.0
7	20358.0	14424.0
8	24302.0	16716.0
9	26241.0	21862.0
10	27970.0	23049.0

The analysis results shown in TABLE II clearly indicate that the first natural frequency in fixed condition (3961.4 Hz) and that in simply supported condition (2234.3 Hz) is well above the engine exciting frequency (1000 Hz). Hence this design is safe. The mode shapes observed for the first four modes in TABLE II are also shown in Figure 7.

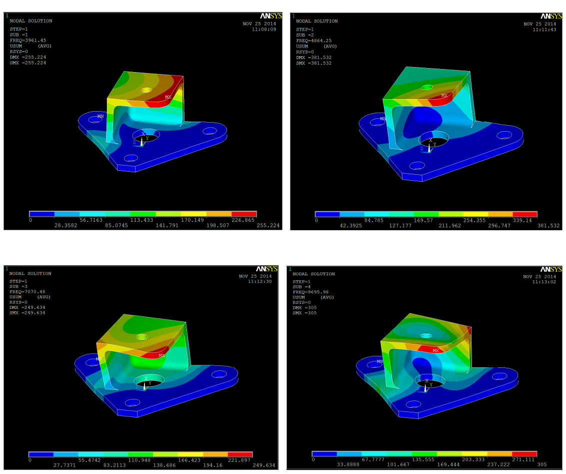

Figure 7 First four mode shapes of the accelerometer mounting bracket

E. Signal Conditioning

Here, accelerometer used is Endevco Isotron, Integrated Circuit Piezoelectric (ICP) type with built in amplifier to suit the transducer output to the input characteristics of the Analog to Digital Converter (ADC). The ADC provides a constant source current excitation per channel of 3.6mA to the accelerometer. A user programmable anti aliasing filter (low pass filter) is incorporated in the ADC card.

F. Data Acquisition Hardware

Data acquisition is a process of gathering information from a physical phenomenon in the real world using hardware and software components in order to present, analyze or store the data in a computer [11]. Independent data logger type DAQ hardware unit, ACRA Control KAM-500 from Curtiss-Wright Corporation is used in this case. One of its major advantages is that it is highly configurable system and enables fully customized systems to be built.

1) Sampling: The analog output of the transducer is sampled at discrete intervals of time. This sampling frequency determines the quality of the results. For appropriate digital representation of the analog signals the sampling rate should be at least twice the largest frequency as per Nyquist theorem. The sampling frequency used here is 2048Hz.

2) Analog to digital conversion: The ADC is an electronic device that converts the analog input signals into a proportional digital signal [12]. ADC116 from ACRA Control KAM-500 [13] is used for analog to digital conversion (Figure 8). This encoded data is stored in ASCII format and can be retrieved for further signal processing. Specifications of the ADC are given in TABLE III.

TABLE III
ADC SPECIFICATIONS

No. of input channels	12
Resolution	16 bit
Input voltage range	±10V
Max. sampling rate	Up to 12000 samples/s per channel

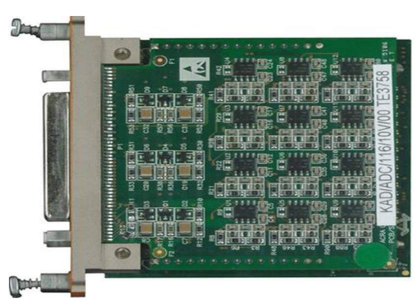

Figure 8 ACRA Control KAM-500 ADC 116 [13]

G. Signal Processing

The signal acquired from the transducer is a composite signal with mix of various magnitudes, frequencies and phase relationships. This waveform signal has to be further processed in order to determine the characteristic features of interest. The vibration signal data acquired at different test runs is stored and post processing is carried out using a commercial signal processing software Prosig DATS-lite Analysis which is a Graphical User Interface (GUI) based interactive platform (Figure 9 & 10). The raw vibration data is imported in the ASCII form and Fast Fourier Transform (FFT) is performed on the time domain signal to convert it to frequency domain. The maximum RMS acceleration and the corresponding frequency are then obtained from the RMS spectrum. These values are determined and recorded for each test run performed on the aircraft engine.

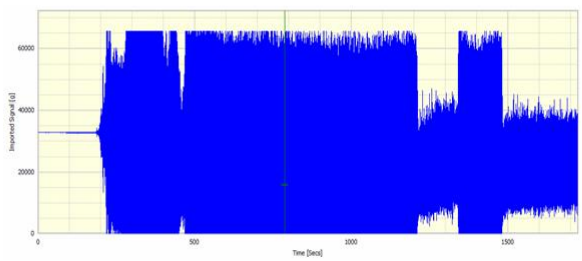

Figure 9 Time domain signal - Prosig DATS-lite Analysis

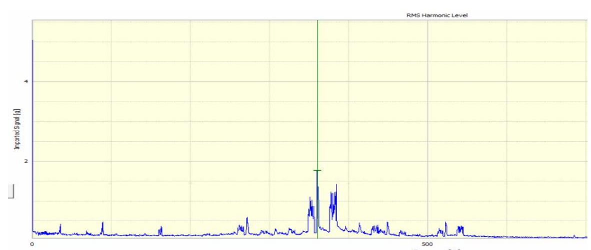

Figure 10 Frequecy spectrum - Prosig DATS-lite Analysis

III. VIBRATION TREND ANALYSIS AND RESULTS

Vibration trend monitoring technique is most widely used for the assessment of engine health monitoring. Any changes in the trend will alert the analyst regarding the developing problem. Here, the peak acceleration level is determined and plotted against each ground run performed on the engine. But, to conduct a detailed diagnostic analysis further processing of the signal and extraction of more characteristic features is essential.

H. Description of the Test Condition

1) Test Condition: Tests are performed on the aircraft in static condition and it is termed as Engine Ground Run (EGR). The test conditions for each event of every EGR are predefined. Engine Start up to Cruise Power setting (i.e. 40% Torque); where vibration levels are dominant are taken into consideration for analysis.

2) Vibration Limits: The vibrations measured at the locations A, B, C and D should not exceed the limits specified by the engine manufacturer. Also care should be taken so that the equipment used for verification must not be subject to natural frequency resonance within the range specified. The vibration limits are shown in Fig. 10 and allowable steady state vibration limit is 2.5 Pk-g.

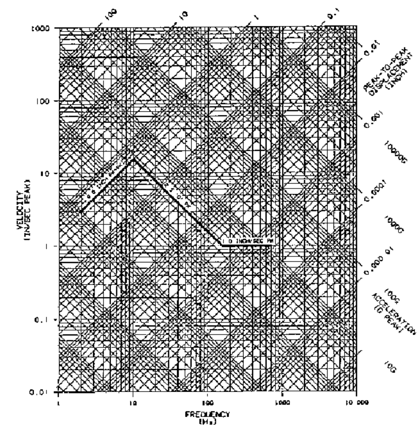

Figure 11 OEM recommended vibration limits [8]

I. Vibration Trend Plot

The peak acceleration (Pk-g) values from all the sensors are plotted for each EGR and the trend curve is obtained. The signal processing of the raw vibration data yields maximum RMS acceleration value and its corresponding frequency (Figure 10). But since the vibration limits given by the engine manufacturer are in terms of peak acceleration (Figure 11), conversion is done using the following formula:

$$\text{Peak acceleration} = \text{max. RMS acceleration} * 1.414$$

The Pk-g accelerometer values are calculated and tabulated as shown in the TABLE IV and TABLE V.

TABLE IV
EGR SUMMARY EGR_45ï LH ENGINE

Accelerometer Position	ABO	AGB	RGB3	RGB6
Max-RMS-g	0.51	0.17	1.26	1.16
Pk-g	0.73	0.24	1.79	1.64

TABLE V
EGR SUMMARY EGR_45ï RH ENGINE

Accelerometer Position	ABO	AGB	RGB3	RGB6
Max-RMS-g	1.09	0.205	0.69	0.80
Pk-g	1.54	0.29	0.98	1.13

Similarly, the vibration testing is carried out for 45 EGR and the data acquired is processed to determine the Pk-g acceleration level. Further, the Pk-g acceleration is plotted against corresponding EGR to yield the vibration trend plot shown in Figure 12 and Figure 13.

J. Analysis and Inference

The vibration trend plot for both the RH and LH engine gives the vibration level at locations where the accelerometers are mounted. Vibration levels are lowest at the location D besides the accessory gearbox (AGB) for both the engines. The sensors at the reduction gearbox (RGB) location (B and C) show high levels of vibration in both RH and LH engines as the RGB is close to the one of the main vibration source i.e. propeller. Accelerometer at location A in RH engine and that at location B in LH engine shows some cases of high vibrations above the safe limits. To determine the root cause of this upward trend seen in the Figure 12 and Figure 13, a detailed study has been carried out which has revealed many useful maintenance actions. To isolate the engine damage due to vibration limit exceedance, engine main parameters such as compressor rpm, turbine temperature, torque limits, engine oil temperature etc were assessed for that particular test condition and engine performance was found to be normal and satisfactory.

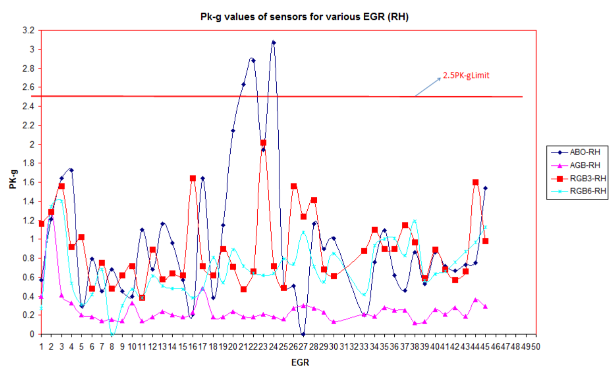

Figure 12 Vibration trend plot ï RH engine

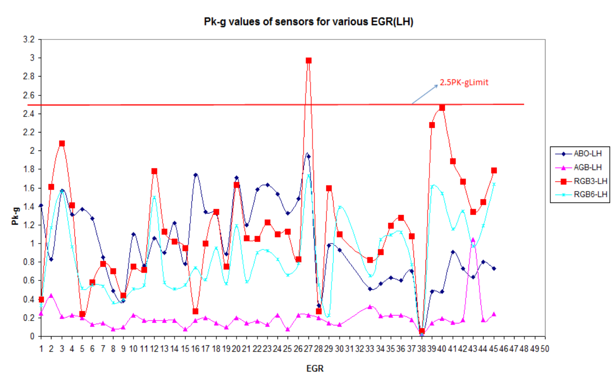

Figure 13 Vibration trend plot ï LH engine

Further, up on inspection of the particular accelerometers it is found that accelerometer mating connector was improper in one case and accelerometer mounting bracket fasteners were unthreaded due defective thread profile in the other case. These studies have helped the engine maintenance team to take pro-active maintenance actions before it leads to actual failures.

IV. CONCLUSION

The main objective was measuring the vibration signals generated by a light transport aircraft engine after its installation to verify if it is within the level specified by the OEM. The study is also set out to design a suitable transducer mounting bracket and analyze it for its dynamic performance. The architecture of the data acquisition system is studied and the trend curve is plotted from the vibration signal data gathered during the EGR. It has been found that the vibration measurement system described is able to successfully indicate any abnormal operating conditions with an upward trend and alert the analyst to give input to the engine maintenance team for further corrective action.

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